

Article

Free-Supported Geopolymer-Based NaA Zeolite Membrane for PGME Dehydration Purification

Xia Deng ¹, Lemin Huang ², Yunfei Mo ² and Xuemin Cui ^{2,*}¹ Guangxi Minzu University, Nanning 530006, China; jwcsyk@gxmzu.edu.cn² Guangxi Key Lab of Petrochemical Resource Processing and Process Intensification Technology, School of Chemistry & Chemical Engineering, Guangxi University, Nanning 530004, China; 2414391070@st.gxu.edu.cn (Y.M.)

* Correspondence: cuixm@gxu.edu.cn

Abstract

Self-supported gradient bilayer NaA zeolite membranes were hydrothermally converted from geopolymer precursors for pervaporative dehydration of the propylene glycol methyl ether (PGME)/water azeotrope. XRD confirms crystallization of amorphous geopolymer into NaA zeolite. The 9 mm-thick membrane comprises a thin surface NaA-selective layer and a porous substrate providing low-resistance feed transport. The membrane shows preferential water adsorption and separates via the adsorption–diffusion mechanism. Performance depends on feed temperature and PGME concentration. At 30 °C and 95 wt% PGME, it achieves a flux of 1.1 kg·m^{−2}·h^{−1} and an ultrahigh separation factor of 2695, far exceeding conventional PVA membranes. This low-cost membrane demonstrates excellent potential for lab-scale organic solvent dehydration.

Keywords: adsorption; diffusion; geopolymers; pervaporative separation; self-supported zeolite membrane

1. Introduction

In recent decades, zeolite membranes have attracted considerable attention because of their potential application in separation membranes, catalytic membrane reactors, and chemical sensors [1–6]. There has been success in forming MFI-, FAU-, and LTA-type zeolites as separation membranes [7–11]. NaA zeolite has been used as a molecular sieve with a pore size of 0.4 nm. Because NaA is hydrophilic, zeolite membranes of this material can separate water from aqueous/organic mixtures or be used in seawater desalination [12–16]. Therefore, NaA membranes that are highly selective and permit a high flux are strongly desired in the separation industry [12–16].

However, the disadvantage of classical zeolite membranes is the high price of the ceramic or metal supports because of the high-temperature sintering manufacturing [7–16]. Geopolymers, first named by Davidovits in 1978 [17], are non-crystalline or quasi-crystalline inorganic polymer gels with a network of three-dimensional structures [17–22], which can transform into zeolite crystal under suitable composition and hydrothermal process. Although our previous work [18,19] demonstrated the successful fabrication of self-supported NaA zeolite membranes from geopolymers and their application in ethanol/water separation, the application of such membranes for PGME dehydration has not been explored. Given the azeotropic nature of the PGME/water system and the increasing industrial demand for energy-efficient purification of this green solvent, the present study provides the first systematic investigation of PGME dehydration using geopolymer-based NaA zeolite



Academic Editors: Mikel Añibarro-Ortega and José Pinela

Received: 28 June 2026

Revised: 19 July 2026

Accepted: 22 July 2026

Published: 25 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

membranes. This work not only extends the application scope of these low-cost membranes but also provides new insights into the adsorption-diffusion behavior of PGME/water mixtures through NaA zeolite channels.

Propylene glycol monomethyl ether (PGME) is known as a universal green solvent because of its low toxicity and excellent performances. The azeotrope of water and PGME occurs at 99.6 °C. The structure of PGME is more complex and larger than that of water molecules. General distillation methods cannot separate the PGME/water mixture effectively, and using such methods results in a large energy consumption and high cost [23–26]. In the late 2000s, pervaporation technology presented several new advantages, such as low operating temperatures, small floor space, low energy consumption, and environmentally friendly usage. However, this technology has mainly been used for separating isotropic systems and near-boiling, isomeric, and heat-sensitive liquids, for which the organic membrane is not suitable for the pervaporation separation process [1–6]. Thus, exploring the economic and environmental benefits of zeolite membrane pervaporation technology for PGME separation is imperative.

2. Experimental Procedure

Based on previous work [18,19], the fabrication route of free-supported NaA zeolite membranes is illustrated in Figure 1. Na-geopolymer precursors were prepared using synthetic Al_2O_3 – SiO_2 powder, sodium silicate solution ($\text{SiO}_2/\text{Na}_2\text{O}$ molar ratio = 1.0), diluted from 39 wt% waterglass (Chunxu Chemical Co., Ltd., Nanning, China) with an original $\text{SiO}_2/\text{Na}_2\text{O}$ molar ratio of 3.15, and sodium hydroxide (Guanghua Sci-Tech Co. Ltd., Guangdong, China). These raw materials were mixed with distilled water at a solid–liquid mass ratio of 1.0 to form geopolymer slurry with a molar composition of Al_2O_3 – 2SiO_2 – Na_2O . The homogeneous paste was cast into 40 mm-diameter disk molds, and the membrane thickness was controlled by adjusting paste volume; the final geopolymer green body obtained after demolding had a thickness of 9.0 mm. Sealed molds were cured at 60 °C for 24 h, then the geopolymer disks were transferred to Teflon-lined autoclaves with 50 mL deionized water and hydrothermally treated at 90 °C for 6 h to yield crystalline free-supported NaA zeolite membranes.

Membrane microstructure was characterized by XRD and SEM. N_2 adsorption–desorption tests at 77 K on a Micromeritics 3Flex instrument (Micromeritics Instrument Corporation, Norcross, GA, USA) were used to analyze micropore and mesopore structures. Before testing, all samples were vacuum-degassed at 250 °C for 48 h under vacuum below 1×10^{-3} Pa to remove adsorbed impurities. The BET method calculated specific surface area, and the BJH model derived meso/micropore size distributions from desorption branches. Mercury intrusion porosimetry (MIP, AutoPore IV 9500, Micromeritics Instrument Corporation, Norcross, GA, USA) was adopted to characterize macropores: samples were dried at 120 °C for 12 h to remove free surface water, with intrusion pressure ranging from 0.01 to 400 MPa, mercury contact angle of 140°, and surface tension of 485 mN/m for pore size calculation.

Pervaporation (PV) performance was measured on a self-assembled lab-scale PV apparatus (Figure 2) using PGME/water mixtures, with feed pressure maintained below 0.1 MPa. All tests employed 40 mm-diameter disk membranes with a total thickness of 9.0 mm and an effective permeation area of 12.57 cm²; PTFE gaskets were used for full edge sealing to avoid leakage. The downstream side was kept under vacuum below 0.01 MPa, and each batch ran continuously for at least 4 h to reach a stable permeation state. Permeate vapor was condensed and collected in liquid nitrogen cold traps, and the mass fractions of PGME and water in feed and permeate were quantified by GC equipped with a thermal

conductivity detector (GC-TCD, Agilent 7890A, Agilent Technologies, Santa Clara, CA, USA). Three core PV indexes were calculated as follows [13,14,19]:

$$J = m/At, \quad (1)$$

$$\alpha = c(1 - c_0)/[c_0(1 - c)], \quad (2)$$

$$PSI = J\alpha, \quad (3)$$

where m is the fluid volume that penetrated a membrane; A is the effective membrane area; t is the pervaporation time; J is the permeation flux; α is the separation factor; and c_0 and c are the PGME mass concentrations of the feeding and penetrating fluids, respectively.

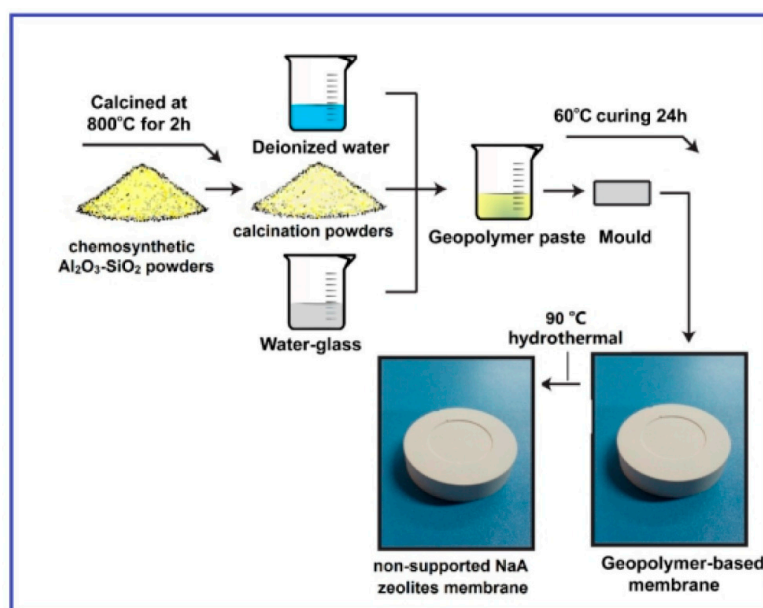


Figure 1. Schematic of the preparation process of non-supported zeolite membrane, embedded photos.

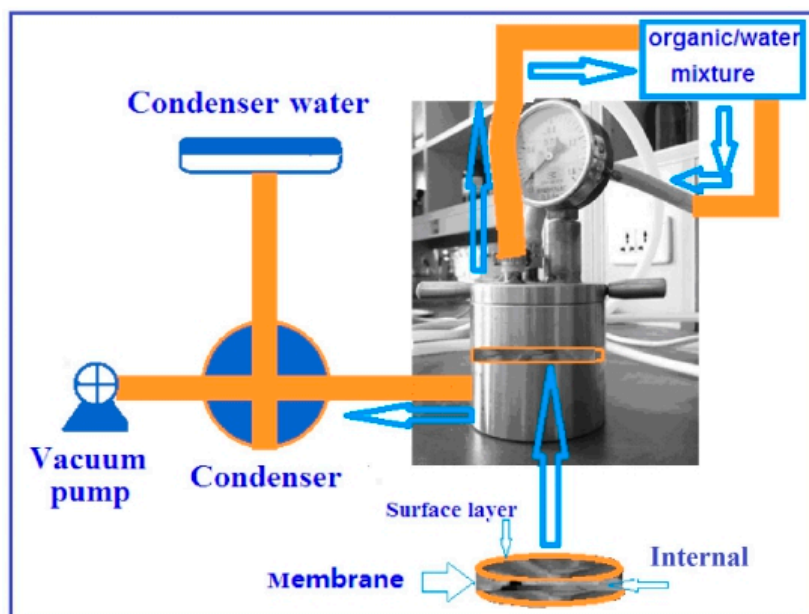


Figure 2. Schematic of the pervaporation process for PGME/water using a non-supported zeolite membrane.

3. Results and Discussions

3.1. Influences of the Membrane Structure on the Pervaporation Mechanism

The phase composition, framework structure, microscopic morphology, and pore structure of the as-fabricated self-supported NaA zeolite membrane were systematically characterized via XRD, FTIR, SEM, N₂ adsorption–desorption (BET), and mercury intrusion porosimetry. As displayed in Figure 3a, the geopolymers before hydrothermal treatment exhibit a broad diffuse amorphous halo centered at $2\theta = 24.5^\circ$, evidencing their intrinsically non-crystalline nature with a faint crystallization tendency. After hydrothermal conversion, this broad amorphous signal disappears entirely, accompanied by a set of well-defined sharp diffraction peaks that perfectly match the standard pattern of LTA-type NaA zeolite (PDF No. 39-0222). This observation confirms that the geopolymer gel undergoes complete structural rearrangement to form pure crystalline NaA zeolite during hydrothermal treatment [22].

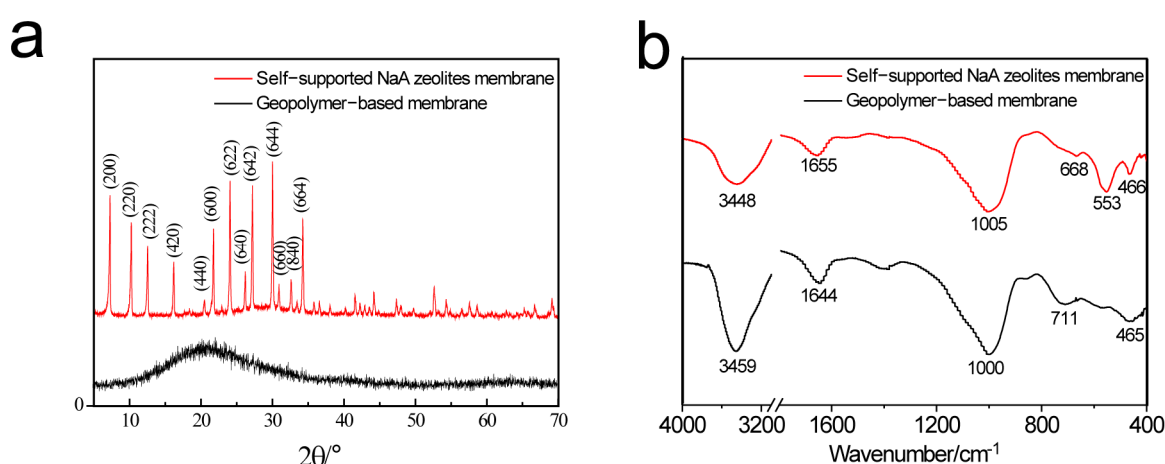


Figure 3. XRD (a) and FTIR (b) spectra of geopolymer-based membrane and self-supported NaA zeolite membrane.

FTIR spectra further reveal the evolution of the Si–O–Al framework from geopolymer to self-supported NaA zeolite membrane (Figure 3b). Both geopolymer and zeolite samples exhibit characteristic absorption bands at $3410\text{--}3459\text{ cm}^{-1}$ and $1644\text{--}1655\text{ cm}^{-1}$, corresponding to O–H stretching and bending vibrations of Si–OH, Al–OH, and adsorbed water, demonstrating the inherent hydrophilicity of both frameworks. The pristine geopolymer presents a Si–O–Si symmetric stretching peak at 711 cm^{-1} . After hydrothermal conversion, zeolite vibration bands appear at 1005 cm^{-1} , 668 cm^{-1} , 553 cm^{-1} , and 466 cm^{-1} , which are assigned to tetrahedral asymmetric stretching, tetrahedral symmetric stretching, external double-four-ring linkage vibration, and internal T–O bending vibration, respectively [4,22]. Except for the newly generated double-four-ring structural vibration, most framework vibration modes are inherited from the original geopolymer precursor, indicating that the NaA zeolite is in situ transformed with retention of the fundamental aluminosilicate skeleton.

The microscopic morphology of the membrane is displayed in Figure 4a,b. Irregular surface pores are formed due to inhomogeneous water evaporation during membrane curing. Cross-sectional SEM observations show uniformly distributed polyhedral NaA crystals with high crystallinity. Abundant intercrystalline voids are formed among zeolite grains, providing favorable mass-transfer channels for molecular permeation.

For pervaporation through the zeolite membrane, the effective separation was determined by the non-zeolitic pores [7–16,19], as fewer non-zeolitic pores and smaller pore sizes resulted in a higher separation factor. N₂ adsorption–desorption measurements were

performed to quantitatively analyze the micro- and mesopore structure (Table 1). After hydrothermal crystallization, the specific surface area increased sharply from 7.17 m²/g to 105.45 m²/g. Notably, the micropore surface area increased from 0 to 101.99 m²/g, while the external mesopore surface area decreased from 7.17 m²/g to 3.46 m²/g. This variation indicates that the amorphous geopolymer structure was reconstructed and converted into a micropore-dominated crystalline NaA framework. The average mesopore diameter remained stable at approximately 3.25 nm for both samples. In addition, the BET C-constant increased significantly from 42.5 to 186.3 after crystallization, demonstrating enhanced surface adsorption affinity originating from the formation of well-defined zeolite micropores.

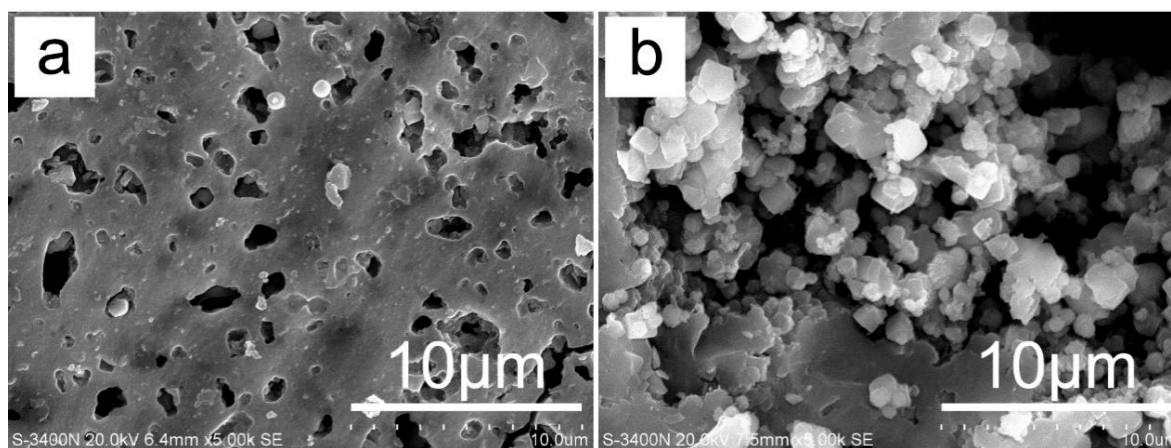


Figure 4. SEM micrographs of self-supported NaA zeolite membrane: (a) surface; (b) cross-sectional.

Table 1. Material properties of the geopolymer and hydrothermal samples.

Sample	Micropore Area m ² /g	Mesopore Area m ² /g	Mesopore Diameter Dv(d) nm	BET Surface Area m ² /g	BET C-Constant
Geopolymers	0	7.17	3.25	7.17	42.5
Hydrothermal samples	101.99	3.46	3.98	105.45	186.3

Mercury intrusion porosimetry was further used to characterize the interzeolitic macro- and mesopore distribution of the self-supported membrane (Figure 5). The internal pore structure is dominated by mesopores (10–20 nm) and macropores (1.5–3.5 μm), with an average overall pore radius of approximately 7.0 nm. Macropores mainly originate from residual bubbles during geopolymer curing, whereas mesopores are generated from polycondensation and dehydration. Such non-zeolitic pores can be further optimized by vacuum defoaming, and a suitable membrane thickness of 9.0 mm was adopted in this work to balance high flux and high separation factors, according to our previous studies.

The unique hydrophilic framework, well-developed micropore structure, and hierarchical pore system endow the NaA zeolite membrane with excellent water-selective adsorption performance. As shown in Figure 6, the NaA zeolite membrane exhibits preferential adsorption toward water rather than PGME in the binary solution. The adsorbed water capacity reaches approximately 2.6 g, while PGME adsorption is only 0.5 g. As a highly hydrophilic LTA-type zeolite, NaA possesses a strong affinity toward polar water molecules but weak interaction with weakly polar PGME. Consequently, water molecules are preferentially adsorbed and concentrated within the zeolite framework, while PGME

adsorption is largely suppressed. This distinct selective adsorption behavior confirms the excellent water-absorbing capacity of the fabricated NaA zeolite membrane, providing a fundamental structural basis for efficient PGME/water pervaporation separation.

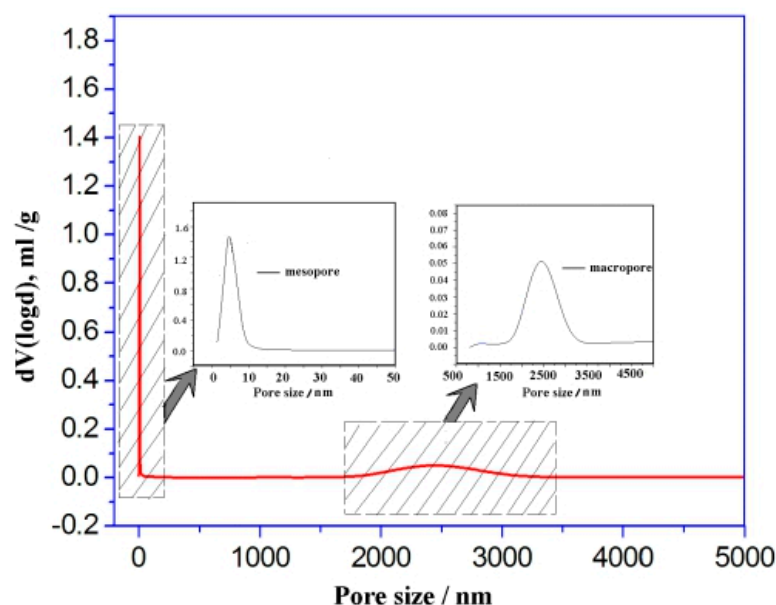


Figure 5. The non-zeolitic pore size distribution curve as determined by a mercury injection apparatus.

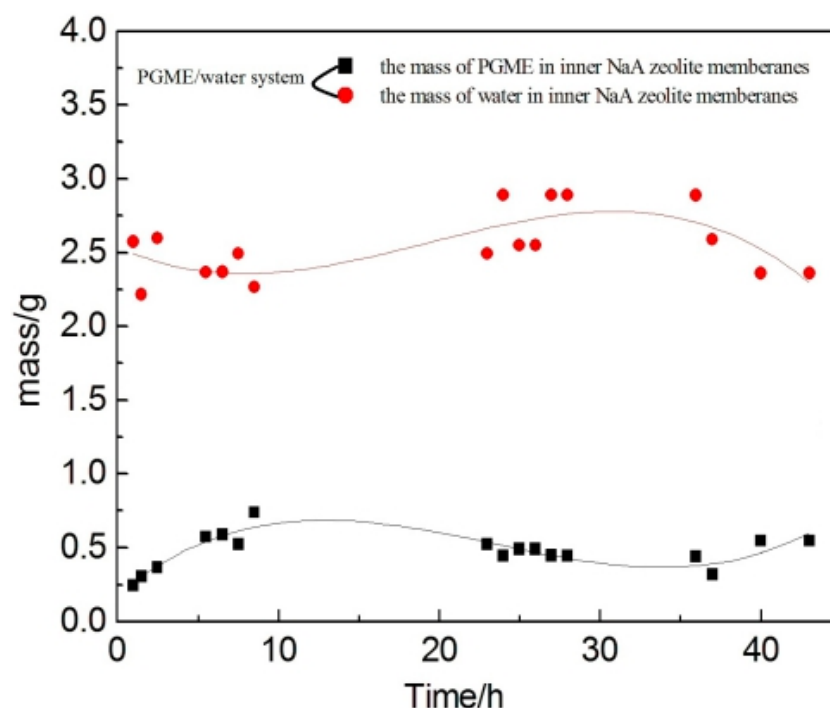


Figure 6. Adsorption equilibrium curves of PGME and water on self-supported NaA geopolymer membrane at 30 °C.

3.2. Impact of the Equilibrium Adsorption on the Pervaporation Mechanism

In the pervaporative separation of organic/water mixtures with NaA zeolite membranes, the ionic sites in the NaA zeolite play an important role in the transport mechanism [9,10,15]. The activated surface diffusion of water through the membrane correlates linearly with the partial pressure driving force, which originates in the separation of solutes. The transport of water through the NaA zeolite matrix is composed of three

steps [9,10,15,19]: (i) strong adsorption of the species on the zeolite cage, (ii) surface diffusion of the species from cage wall to cage wall, and (iii) vaporization of the species on the permeate side. Normally, any physical adsorption process includes both van der Waals dispersion-repulsion forces and electrostatic forces, which consist of polarization, dipole, and quadrupole interactions. The transport mechanism behind PV diffusion through self-supported NaA zeolite membranes was explained by the adsorption–diffusion model [27,28].

To quantitatively elucidate the selective adsorption–diffusion mechanism of the self-supported NaA zeolite membrane, dynamic adsorption tests were performed at 30 °C using pure water and 83 wt% PGME aqueous solution. As shown in Figure 7a, the PGME concentration remained nearly constant during adsorption, demonstrating negligible adsorption affinity of the NaA membrane toward PGME molecules, which is consistent with the intrinsic water-preferring property of hydrophilic LTA zeolite. Figure 7b presents the time-dependent water adsorption behavior in pure water. The water uptake increased rapidly, slightly declined, and finally reached equilibrium, exhibiting a consistent adsorption trend with that in PGME aqueous solution. The membrane achieved a maximum water adsorption capacity of $2.73 \text{ g} \cdot (\text{g zeolite})^{-1}$ within 13.7 h in pure water, whereas the maximum adsorption was delayed to 25 h in the PGME-containing system. This delayed equilibrium indicates that PGME molecules produce steric hindrance and occupy partial surface sites, effectively inhibiting water adsorption and diffusion. Such prominent preferential water adsorption provides solid quantitative evidence for the adsorption–diffusion mechanism and fundamentally accounts for the excellent PGME dehydration performance of the fabricated NaA zeolite membrane.

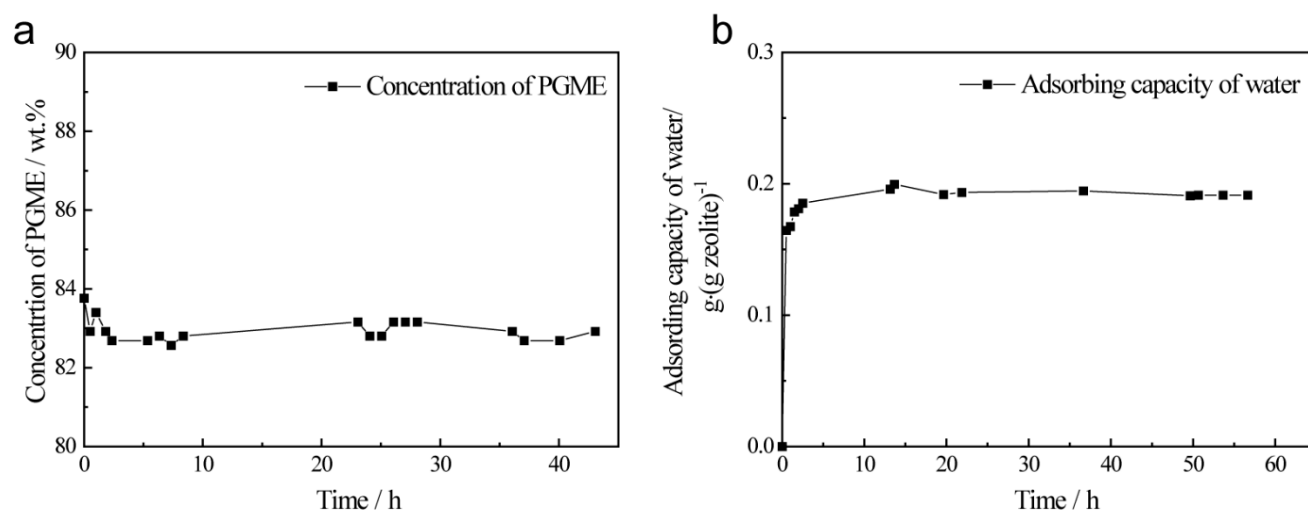


Figure 7. Dynamic adsorption curves of the NaA zeolite membrane at 30 °C: (a) Variation in PGME concentration over time in 83 wt% PGME solution; (b) Time evolution of water adsorption capacity in pure water.

Notably, despite its 9.0 mm total thickness, the monolithic membrane does not suffer from reduced permeation flux due to its gradient bilayer structure. The selective layer is merely a micrometer-thick NaA zeolite film on the surface, while the thick geopolymer support contains abundant interconnected macropores that act as unobstructed channels to deliver feed to the active layer. This thickness, optimized for mechanical stability, successfully minimizes diffusion resistance for the permeate vapor, thereby maintaining a high flux even at such a large bulk scale.

3.3. Impact of PV Parameters on the Pervaporation Performance

Figure 8 showed the relationship between temperature (feeding temperatures were 30 °C, 40 °C, 50 °C, 60 °C, and 70 °C) and separation factor. According to the “solution—diffusion” theory, the temperature increase facilitated the PGME molecules’ activity on the membrane surface and allowed them to diffuse through the membrane [26]. At the same time and because of the high temperature, the free volume of the interior membrane and the pore structures increased. This reduced the ability of the NaA zeolite membrane to selectively separate PGME molecules. So, the separation factor decreased with the temperature increment, and the higher the temperature was, the smaller the difference between the temperature and the separation factor was.

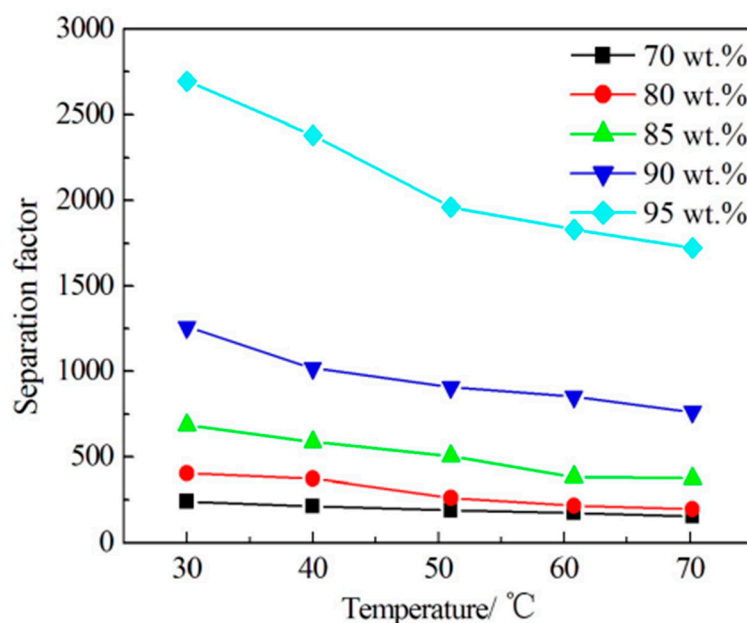


Figure 8. Effect of temperature on the separation factor with different concentrations of PGME in the feed.

Next, the pervaporation experiment with PGME ($c = 95$ wt%) was performed at different temperatures. The effects of the feed temperature on the flux with 95 wt% PGME in the feed are displayed in Figure 9. The total flux and partial flux of PGME increased with increasing feed temperatures because of the increased activity of the components in the mixture and the accelerated rate of molecular diffusion. Due to the high concentrations of PGME, the number of water molecules in the feed was reduced; so, the partial flux of water was small and slowly increased with temperature.

Figure 10 showed the effect of the feed concentration (70 wt%, 80 wt%, 85 wt%, 90 wt%, and 95 wt%) on the separation factor. The size of the pores in the NaA membrane was bigger than the diameter of the water molecule but far less than the size of PGME, so only the water molecules could migrate through the hydrophilic membrane. The speed at which the water molecules traveled into the zeolite pores decreased, as some pores were blocked by PGME molecules at higher concentrations of PGME. Therefore, the separation factor increased with the increase in the feed concentration. At the same time, this positive trend was more apparent as the concentration increased.

The relationships between the contents of the PGME/water mixture and the flux at 30 °C are shown in Figure 11. As the concentration of PGME increased, the uptake of water molecules into the NaA zeolite membrane was reduced, which lowered the water diffusion rate and partial flux. Additionally, the greater the competition for the absorption and diffusion of PGME molecules, the smaller the amount of PGME that passes into the

NaA zeolite membrane. As a result, the flux of PGME decreased to values lower than those of water.

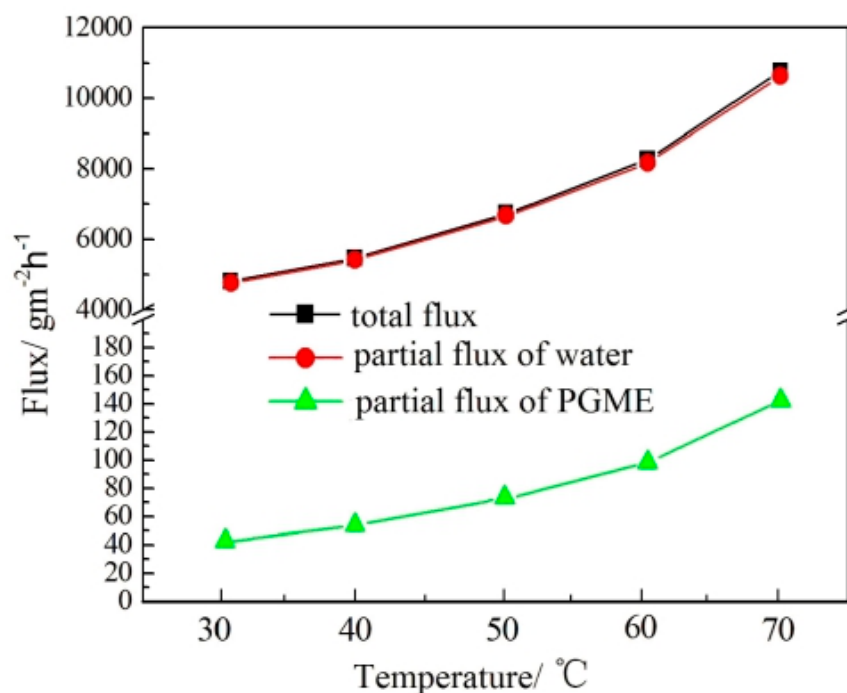


Figure 9. Effect of temperature on flux with 95 wt% PGME in the feed.

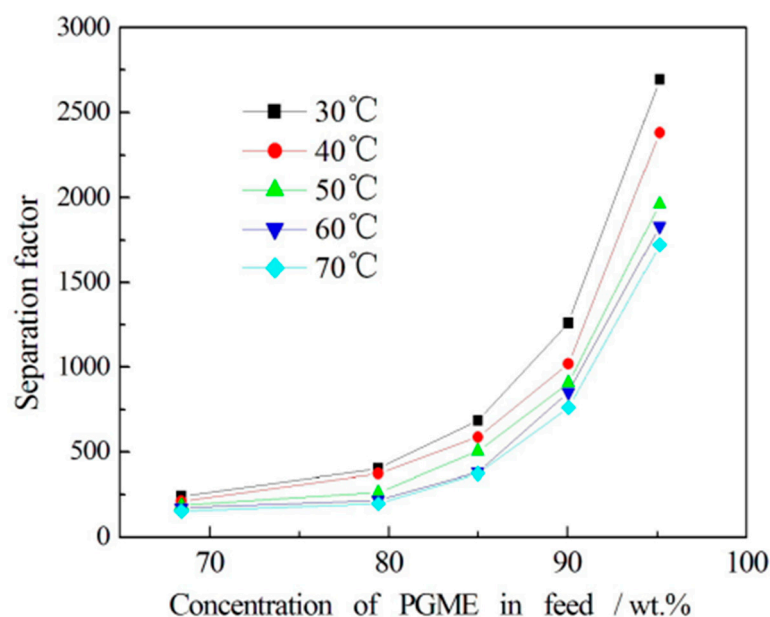


Figure 10. Effect of the concentration of PGME in feed on the separation factor at different temperatures.

As shown in Table 2, the comparison of the separation performances for aqueous PGME solutions between the PVA membrane and the self-supported NaA zeolite membrane revealed that the high separation factor and separation index for PGME were related to their low adsorption in the membrane materials. Furthermore, the NaA zeolite membrane possessed higher separation efficiency at a lower cost when compared with a traditional PVA membrane. Therefore, the self-supported NaA zeolite membrane may be useful for applications in the dehydration field.

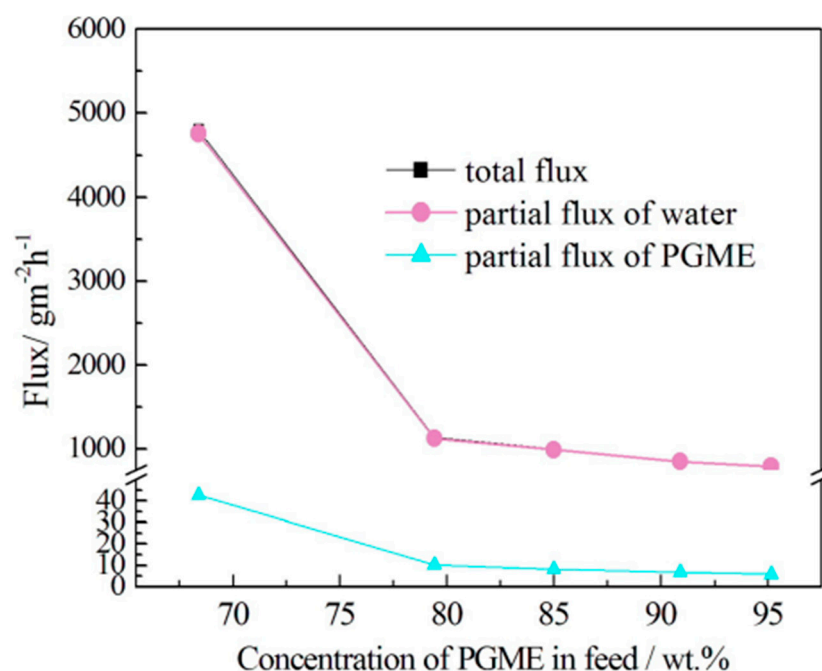


Figure 11. Effect of the concentration of PGME in feed on the flux at 30 °C.

Table 2. Comparison between PVA membrane and self-supported NaA zeolite membrane.

Membrane Separation for 95 wt% PGME at 30 °C	Flux g/m ² h	Separation Factor	Separation Index
PVA membrane	332	7.5	2500
Self-supported NaA zeolites membrane	1100	2695	2,964,500

4. Conclusions

Self-supported NaA zeolite membranes were prepared via geopolymer hydrothermal conversion for PGME/water pervaporation dehydration. Characterizations verified pure surface NaA zeolite and a gradient bilayer structure: a micrometer-thin selective zeolite film covers the 9.0 mm porous geopolymer substrate, which provides low-resistance feed transport without participating in separation. The 9 mm thickness balances mechanical strength and permeation flux. Separation follows the adsorption–diffusion mechanism, where NaA preferentially adsorbs water over PGME. At 30 °C with 95 wt% PGME feed, the membrane delivers a flux of 1.1 kg·m^{−2}·h^{−1} and a separation factor of 2695, greatly superior to PVA membranes. This low-cost membrane exhibits excellent single-run lab-scale dehydration performance, yet data on cyclic stability, regeneration, and pressure resistance are missing. Further industrial-relevant tests will be carried out in follow-up work to validate its practical application potential.

Author Contributions: Conceptualization, X.C.; Methodology, X.D., L.H. and Y.M.; Software, X.D.; Validation, X.D. and L.H.; Formal analysis, Y.M.; Investigation, X.D. and L.H.; Resources, X.C.; Data curation, X.D.; Writing—original draft, X.D.; Writing—review and editing, X.C.; Visualization, L.H. and Y.M.; Supervision, X.C.; Project administration, X.C.; Funding acquisition, X.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Chinese Natural Science Fund (grants: 21566006 and 51772055) and the project was sponsored by the Guangxi Natural Science Fund (grants: 2016GXNS-FGA380003 and 2014GXNSFBA118250).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Algieri, C.; Drioli, E. Zeolite membranes: Synthesis and applications. *Sep. Purif. Technol.* **2021**, *278*, 119295. [\[CrossRef\]](#)
- Akhmetzhanova, D.; Sabitov, A.; Doszhanov, Y.; Atamanov, M.; Saurykova, K.; Zhumazhanov, A.; Atamanova, T.; Kerimkulova, A.; Velasco, L.F.; Zhumagalieva, A.; et al. Zeolites and Activated Carbons in Hydroponics: A Systematic Review of Mechanisms, Performance Metrics, Techno-Economic Analysis and Life-Cycle Assessment. *Sustainability* **2025**, *17*, 10977. [\[CrossRef\]](#)
- Yue, B.; Liu, S.; Chai, Y.; Wu, G.; Guan, N.; Li, L. Zeolites for separation: Fundamental and application. *J. Energy Chem.* **2022**, *71*, 288–303. [\[CrossRef\]](#)
- El-Sayed, A.M.; Abdallah, H.; Abdel-Goad, M.; Abobeah, R.; Amin, S.K. Preparation and optimization of eco-friendly inorganic geopolymer membrane. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 16021–16042. [\[CrossRef\]](#)
- Lee, J.; Patel, R. Zeolite Based Pervaporation Membrane: A Review. *Membr. J.* **2022**, *32*, 383–389. [\[CrossRef\]](#)
- Luo, R.; Ding, H.; Lyu, J.; Fu, T.; Bai, P.; Guo, X.; Tsapatsis, M. Fabrication of a sandwiched silicalite-1 membrane in a 2D confined space for enhanced alcohol/water separation. *Chem. Commun.* **2020**, *56*, 12586–12588. [\[CrossRef\]](#) [\[PubMed\]](#)
- Sano, T.; Yanagisaita, H.; Kiyozumi, Y.; Mizukami, F.; Haraya, K. Separation of ethanol/ water mixture by silicalite membrane on pervaporation. *J. Membr. Sci.* **1994**, *95*, 221–228. [\[CrossRef\]](#)
- Kusakabe, K.; Kuroda, T.; Murata, A.; Morooka, S. Formation of a Y-type zeolite membrane on a porous α -alumina tube for gas separation. *Ind. Eng. Chem. Res.* **1997**, *36*, 649–655. [\[CrossRef\]](#)
- Vroon, Z.A.E.P.; Keizer, K.; Gilde, M.J.; Verweij, H.; Burggraaf, A.J. Transport properties of alkanes through ceramic thin zeolite MFI membranes. *J. Membr. Sci.* **1996**, *113*, 293–300. [\[CrossRef\]](#)
- Kondo, M.; Komori, M.; Kita, H.; Okamoto, K. Tubular-type pervaporation module with zeolite NaA membrane. *J. Membr. Sci.* **1997**, *133*, 133–141. [\[CrossRef\]](#)
- Braunbarth, C.M.; Boudreau, L.C.; Tsapatsis, M. Synthesis of ETS-4/TiO₂ composite membranes and their pervaporation performance. *J. Membr. Sci.* **2000**, *174*, 31–42. [\[CrossRef\]](#)
- Gao, X.; Gao, B.; Liu, H.; Zhang, C.; Zhang, Y.; Jiang, J.; Gu, X. Fabrication of stainless steel hollow fiber supported NaA zeolite membrane by self-assembly of submicron seeds. *Sep. Purif. Technol.* **2020**, *234*, 116121. [\[CrossRef\]](#)
- Wang, Y.; Rong, H.; Sun, L.; Zhang, P.; Yang, Y.; Jiang, L.; Wu, S.; Zhu, G.; Zou, X. Fabrication and evaluation of effective zeolite membranes for water desalination. *Desalination* **2021**, *504*, 114974. [\[CrossRef\]](#)
- Cho, C.H.; Oh, K.Y.; Kim, S.K.; Yeo, J.G.; Sharma, P. Pervaporative seawater desalination using NaA zeolite membrane: Mechanisms of high water flux and high salt rejection. *J. Membr. Sci.* **2011**, *371*, 226–238. [\[CrossRef\]](#)
- Zhang, Y.T.; Zhu, X.F.; Chen, S.Z.; Liu, J.Y.; Hong, Z.; Wang, J.C.; Li, Z.; Gao, X.C.; Xu, R.; Gu, X.H. TiO₂-decorated NaA zeolite membranes with improved separation stability for pervaporation dehydration of N, N-Dimethylacetamide. *J. Membr. Sci.* **2021**, *634*, 119398. [\[CrossRef\]](#)
- Wang, L.; Yang, J.H.; Wang, J.Q.; Raza, W.; Liu, G.R.; Lu, J.M.; Zhang, Y. Microwave synthesis of NaA zeolite membranes on coarse macroporous α -Al₂O₃ tubes for desalination. *Microporous Mesoporous Mater.* **2020**, *306*, 110360. [\[CrossRef\]](#)
- Davidovits, J. Geopolymers inorganic polymeric new materials. *J. Therm. Anal.* **1991**, *37*, 1633–1656. [\[CrossRef\]](#)
- Liu, Y.; Yan, C.; Zhang, Z.; Li, L.; Wang, H.; Pu, S. One-step fabrication of novel porous and permeable self-supporting zeolite block from fly ash. *Mater. Lett.* **2017**, *196*, 328–331. [\[CrossRef\]](#)
- He, Y.; Cui, X.M.; Liu, X.D.; Wang, Y.P.; Zhang, J.; Liu, K. Preparation of self-supporting NaA zeolite membranes using geopolymers. *J. Membr. Sci.* **2013**, *447*, 66–72. [\[CrossRef\]](#)
- Xu, M.X.; He, Y.; Wang, Y.P.; Cui, X.M. Preparation of a non-hydrothermal NaA zeolite membrane and defect elimination by vacuum-inhalation repair method. *Chem. Eng. Sci.* **2017**, *158*, 117–123. [\[CrossRef\]](#)
- Ge, Y.Y.; Cui, X.M.; Kong, Y.; Li, Z.; He, Y.; Zhou, Q. Porous geopolymeric spheres for removal of Cu(II) from aqueous solution: Synthesis and evaluation. *J. Hazard. Mater.* **2015**, *283*, 244–251. [\[CrossRef\]](#) [\[PubMed\]](#)
- Amari, S.; Darestani, M.; Millar, G.; Boshrouyeh, B. Fabrication and Performance of PVAc-Incorporated Porous Self-Standing Zeolite-Based Geopolymer Membranes for Lead (Pb(II)) Removal in Water Treatment. *Polymers* **2025**, *17*, 1155. [\[CrossRef\]](#) [\[PubMed\]](#)
- Tseng, Y.K.; Gao, G.J.; Chien, S.C. Synthesis of c-axis preferred orientation ZnO: Al transparent conductive thin films using a novel solvent method. *Thin Solid Films* **2010**, *518*, 6259–6263. [\[CrossRef\]](#)
- Li, D.; Sun, X.R.; Li, L.M.; Wang, S.Q.; Wang, L.T.; Liu, X.F. Vapor pressures and volumetric properties for binary mixtures of propylene glycol monomethyl ether and exo-tricyclo decane. *J. Taiwan Inst. Chem. Eng.* **2014**, *45*, 823–827. [\[CrossRef\]](#)

25. Umeda, T.; Sugiyama, S.; Nakamura, T.; Momota, M.; Sevegney, M.; Tsuzuki, S.; Numaguchi, T. Solvent pre-wetting as an effective start-up method for point-of-use filter. *Adv. Resist Mater. Process. Technol.* **XXIX** **2012**, 8325, 629–636. [[CrossRef](#)]
26. Tochigi, K.; Takahara, H.; Shiga, Y.; Kawase, Y. Isobaric vapor–liquid equilibria for water + propylene glycol monomethyl ether (PGME), water + propyleneglycol monomethyl ether acetate (PGMEA), and PGME + PGMEA at reduced pressures. *Fluid Phase Equilibria* **2007**, 260, 65–69. [[CrossRef](#)]
27. Polyakov, Y.S.; Zydney, A.L. Ultrafiltration membrane performance: Effects of pore blockage/constriction. *J. Membr. Sci.* **2013**, 434, 106–120. [[CrossRef](#)]
28. Dubey, V.; Pandey, L.K.; Saxena, C. Pervaporative separation of ethanol/water azeotrope using a novel chitosan-impregnated bacterial cellulose membrane and chitosan–poly(vinyl alcohol) blends. *J. Membr. Sci.* **2005**, 251, 131–136. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.